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Unsaturated elasto-plastic constitutive equations for compacted kaolin under consolidated drained and shearing-infiltration conditions

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Abstract

Transient process of water flow changes the equilibrium conditions of an unsaturated soil, resulting in volume change of a soil. The volume change alters the hydraulic properties of the soil and thus influences the transient process of water flow through the soil. Therefore, the interactive processes between stress-strain behavior and pore-water pressure are the primary processes affecting the mechanical behavior of unsaturated soils. This paper presents coupled elasto-plastic constitutive equations for unsaturated compacted kaolin under consolidated drained and shearing-infiltration conditions. The study focused on the development of the suction increase (SI) yield curve that incorporates changes in matric suction during transient processes. In addition, the relationship of change in specific water volume with respect to net mean stress and matric suction was also proposed by incorporating the hysteresis of soil-water characteristic curve. The simulated results by the proposed constitutive model were compared with those obtained from isotropically consolidated drained tests and shearing infiltration tests of compacted kaolin to verify the proposed model. The simulated results are in close agreement with the experimental results.

Keywords: Elasto-plastic constitutive model; Matric suction; Soil deformation; Hysteresis; Volume change; Unsaturated soils

1. Introduction

A large number of geotechnical problems involve unsaturated soil zones where the voids between soil particles are filled with air and water. There are many practical situations associated with unsaturated soils that are challenging to geotechnical engineers in the field. When fill materials are compacted or loaded, excess pore-air pressure during compaction or loading will dissipate immediately, meanwhile the excess pore-water pressure will dissipate with time. During and after rainstorms the change in pore-water pressure caused by rain water infiltration may result in deformation and instability (Kim et al., 2016)

In the last few decades, a number of theoretical frameworks and constitutive relations based on elasto-plastic theory have been proposed to describe the mechanical behavior of unsaturated soils. These models are capable of reproducing important behavior of unsaturated soils. Alonso et al. (1987, 1990) proposed a general constitutive framework for unsaturated soils. This model was further refined by Toll (1990), Thomas and He (1994), Cui and Delage (1996), Wheeler (1996), Bolzon et al. (1996), Rampino et al. (1999), Simoni and Schrefler (2001), Tang and Graham (2002), Chiu and Ng, 2003, and Thu et al. (2007a). These models were developed based on the independent stress state variables, net normal stress $(\sigma - u_a)$ and matric suction $(u_a - u_w)$ where σ is the total stress, u_a is the pore-air pressure and u_w is the pore-water pressure. On the other hand, there are different assumptions and different constitutive relationships used in these models.

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Wheeler and Sivakumar (1995) proposed an elastoplastic model that is similar to the model of Alonso et al. (1990) but proposed specific water volume as one of the stress state variables for unsaturated soil. Tang and Graham (2002) pointed out that these models are generally developed based on tests on silts, silty clays, or low-plasticity clays such as kaolinite at relatively low and/or constant matric suction. Therefore, it may be termed as a "constant-suction model" and may not provide a complete description of the behavior of compacted, highly plastic soils (Tang and Graham, 2002). Therefore, it would be appropriate to develop elasto-plastic constitutive relations for unsaturated soils that are applicable to a wider range of soil types and boundary conditions.

It has been highlighted that matric suction is an important stress state variable that has a significant influence on yield behavior of unsaturated soils (Fredlund et al., 1996; Vanapalli et al., 1996). Changes in matric suction affect the stress-strain behavior, volume change, and unsaturated shear strength by changing the hydraulic properties of the soil. Thus, many researchers suggested yield loci to define the relation between net mean stress and matric suction. It was noticed that collapse of the soil was closely related to both drying and wetting processes due to the reasons mostly associated with climatic conditions (i.e., rainwater infiltration or evaporation) (Alonso et al., 1990; Wheeler and Sivakumar, 1995).

The main objective of this paper is to present coupled elasto-plastic constitutive equations for unsaturated soil under consolidated drained and shearing-infiltration conditions. The study focused on the development of the suction increase (SI) yield curve that incorporates changes in matric suction during transient processes. In addition, the relationship of change in specific water volume with respect to net mean stress and matric suction was also proposed by incorporating the hysteresis of soil-water characteristic curve. The simulated results by the proposed constitutive model were compared with the experimental results obtained in this study to verify the proposed model.

Statically compacted kaolin specimens were used in this study to carry out the isotropic consolidation tests under different matric suctions, tests for obtaining soil-water characteristic curves under different net mean stresses, consolidated drained triaxial tests, and shearing-infiltration tests for verification of the proposed model.

2. Background for elasto-plastic constitutive relations

An unsaturated soil consists of four phases. When stress gradients are applied, two phases will flow (i.e., air phase and water phase), and the other two phases will come to equilibrium (i.e., soil structure and contractile skin). Volume changes associated with the contractile skin can be assumed to be negligible. Hence, the constitutive relationships for the three phases can be formulated by relating volume changes to changes in stress state variables. In most cases, two constitutive relationships are presented to describe the volume changes associated with an unsaturated soil, one relationship for soil structure (in terms of void ratio or volumetric strain) and another relationship for the water phase (in terms of degree of saturation or water content) (Fredlund and Rahardjo, 1993).

The critical state model is an elasto-plastic constitutive model with elastic behavior when the soil state lies inside the yield surface and plastic strains when the soil state reached the yield surface. The yield surface in saturated soils is represented by a yield envelope in $p-q$ space and a corresponding coupled trace in $p-v$ space. For yielding of unsaturated soils, yield surface should be defined in $p-s$ space for isotropic loading. Thus, many researchers suggest their yield loci to define the relation between net mean stress and matric suction. It was noticed that collapse of the soil occurred during both drying and wetting processes (Gens and Alonso, 1992; Wheeler and Sivakumar, 1995). The yield boundary for unsaturated soils proposed by Alonso et al. (1990) is not continuous and it comes from tests under constant matric suction. Therefore, Tang and Graham (2002) suggested a new yield curve called the Loading-collapse and Suction increase Yield (LSY) curves to consider possible coupling of matric suction-induced hardening. Delage and Graham (1995) argued that the Loading Collapse (LC) and Suction Increase (SI) yield curves should perhaps be coupled.

Alonso et al. (1990) proposed an elasto-plastic model with four state variables: net mean stress (p), deviator stress (q), matric suction (s), and specific volume (v). On the other hand, Wheeler (1996), Rampino et al. (2000), Wang et al. (2002) and Chiu and Ng (2003) indicated that specific water volume (v_w) should be taken into account in the elasto-plastic constitutive framework model. The behavior of unsaturated soil can then be described using five state variables under axisymmetric stress conditions as follows:

$$p = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} - u_a \qquad (1)$$

$$q = \sigma_1 - \sigma_3 \qquad (2)$$

$$s = u_a - u_w \qquad (3)$$

$$v = 1 + e \qquad (4)$$

$$v_w = 1 + S \cdot e \qquad (5)$$

where σ_1, σ_2, σ_3 = total principal normal stresses; e = void ratio; v_w = specific water volume; and S = degree of saturation.

The total strain increment ($d\varepsilon$) is composed of the elastic strain increment ($d\varepsilon^e$) and the plastic strain increment ($d\varepsilon^p$). Volumetric strain increment ($d\varepsilon_v$) and shear strain increment ($d\varepsilon_q$) can be calculated as follows (Alonso et al., 1990):

$$d\varepsilon_v = d\varepsilon^e_{v(p)} + d\varepsilon^e_{v(s)} + d\varepsilon^p_{v(p)} + d\varepsilon^p_{v(s)} \qquad (6)$$

$$d\varepsilon_q = d\varepsilon^e_q + d\varepsilon^p_q \qquad (7)$$

where $d\varepsilon^e_{v(p)}$ is the elastic volumetric strain increment induced by changes in mean net stress, $d\varepsilon^e_{v(s)}$ is the elastic

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